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# Worsened physical condition due to climate change contributes to the increasing hypoxia in Chesapeake Bay

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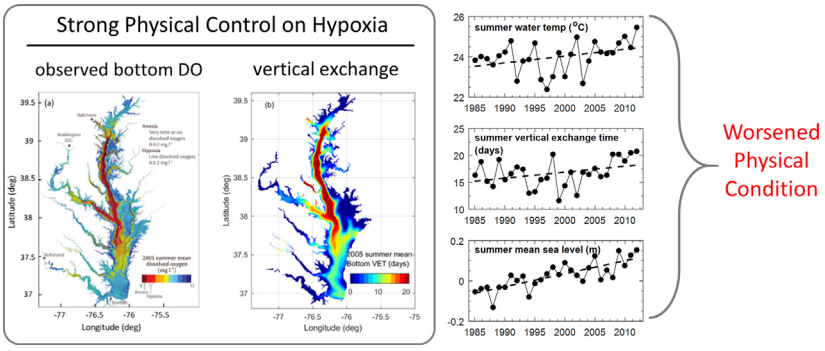
## HIGHLIGHTS

- Analysis of observed data and numerical simulations reveal the great control from physical processes on bottom DO
- Physical processes determine the seasonality and spatial distribution of bottom low DO in Chesapeake Bay
- Physical and biological processes contribute equally on the interannual variability of summer hypoxic volume
- Worsened physical condition (temperature + vertical exchange) in the past decades contributed to the increase of hypoxia

## GRAPHICAL ABSTRACT

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## ABSTRACT

There are increasing concerns about the impact of worsened physical condition on hypoxia in a variety of coastal systems, especially considering the influence of changing climate. In this study, an EOF analysis of the DO data for 1985–2012, a long-term numerical simulation of vertical exchange, and statistical analysis were applied to understand the underlying mechanisms for the variation of DO condition in Chesapeake Bay. Three types of analysis consistently demonstrated that both biological and physical conditions contribute equally to seasonal and interannual variations of the hypoxic condition in Chesapeake Bay. We found the physical condition (vertical exchange + temperature) determines the spatial and seasonal pattern of the hypoxia in Chesapeake Bay. The EOF analysis showed that the first mode, which was highly related to the physical forcings and correlated with the summer hypoxia volume, can be well explained by seasonal and interannual variations of physical variables and biological activities, while the second mode is significantly correlated with the estuarine circulation and river discharge. The weakened vertical exchange and increased water temperature since the 1980s demonstrated a worsened physical condition over the past few decades. Under changing climate (e.g., warming, accelerated sea-level rise, altered precipitation and wind patterns), Chesapeake Bay is likely to experience a worsened physical condition, which will amplify the negative impact of anthropogenic inputs on eutrophication and consequently require more efforts for nutrient reduction to improve the water quality condition in Chesapeake Bay.
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## 1. Introduction

Hypoxia occurs in a variety of coastal environments when dissolved oxygen (DO) is depleted to a certain low level, where aquatic organisms, especially benthic fauna, become stressed or die due to the lack of oxygen (Diaz and Rosenberg, 1995; Levin et al., 2009; Ekau et al., 2010). The threshold of hypoxia is commonly set to 2 mg $O_2$/L, but some researchers (e.g., Vaquer-Sunyer and Duarte, 2008) discussed that this value was not conservative enough and suggested higher values. Hypoxia degrades an ecosystem by damaging the bottom fauna habitats, altering the food web, changing the nitrogen and phosphate cycling, decreasing fishery catch, and enhancing the water acidification (Kemp et al., 1990; Breitburg, 2002; Conley et al., 2009; Melzner et al., 2013). Permanent, seasonal, periodical or episodic hypoxia has been found in >500 coastal systems over the globe, and there is mounting evidence suggesting the duration, intensity, and extent of hypoxia have increased over the past half-century (Boesch et al., 2001; Diaz and Rosenberg, 2008; Rabalais et al., 2010; Breitburg et al., 2018). Hypoxia can occur naturally in bottom waters with restricted vertical mixing and in coastal upwelling regions where low oxygen waters are transported onto continental shelves (Pena et al., 2010). Examples of the systems susceptible to hypoxia include Baltic Sea, Black Sea, northern Gulf of Mexico, Chesapeake Bay, Yangtze River Estuary, Mobile Bay, and oxygen minimum zone in the East Pacific, Atlantic and North Indian Ocean (Hagy et al., 2004; Helly and Levin, 2004; Park et al., 2007; Conley et al., 2009; Rabalais et al., 2010; Chen et al., 2015; Wang et al., 2017).

Although hypoxia has been present throughout geologic time, the occurrence of coastal hypoxia has been accelerated by human activities. The increase of hypoxia over the past half-century is widely attributed to the excessive anthropogenic nutrient loads that stimulate intensified eutrophication (Kemp et al., 2005). To reduce the hypoxic volume, remediation measurements on nutrient loads have been carried out in coastal systems (Boesch et al., 2001; Conley et al., 2009). However, hypoxia in many systems responses to the reduction of nutrient loads in a non-linear way and there is little evidence for simple and straightforward response of hypoxia to remediation actions in both US and European coastal systems, due to various reasons including the changing physical condition and altered ecosystem (Conley et al., 2009; Kemp et al., 2009). There is increasing evidence suggesting the climate change, particularly the global warming, has contributed to the increase of hypoxia in coastal and freshwater systems (Bendtsen and Hansen, 2013; Carstensen et al., 2014; Jenny et al., 2014; Altieri and Gedan, 2015). The climate change has altered the physical condition that determines the sensitivity of the ecosystem to external nutrient and organic matter inputs (Howarth et al., 2011). Understanding the physical control is therefore essential to accurately predict the response of a system to the potential change of physical condition and biological condition, and to manage the water quality and ensure the sustainability of the ecosystem.

Hypoxia primarily results from the imbalance of oxygen replenishment and oxygen consumption. The oxygen consumption comes from two components, the water column microbial decomposition of organic matter and sediment oxygen demand, both of which are related to various biogeochemical processes (Bianchi et al., 2010). In most estuarine systems where seasonal hypoxia occurs, hypoxia usually starts with the enhanced oxygen consumption following the spring algal bloom and the strengthened haline and/or thermal stratification with the increase of freshwater discharge and/or temperature (Boesch et al., 2001). Evaluating the relative contribution of biological and physical control on the seasonal and interannual variation of hypoxia is always challenged by the complex coupling between the physical and biological processes (Caballero-Alfonso et al., 2015). For example, with a large river discharge, both the enhanced stratification and possibly intensified algal bloom stimulated by large nutrient loads contribute to the development of a more serious hypoxia. By setting a constant biological environment (e.g., using a constant DO consumption rate), multiple studies have successfully isolated and investigated the physical impact on hypoxia (e.g., Scully, 2013; Chen et al., 2015; Yu et al., 2015; Du and Shen, 2015; Xia and Jiang, 2015; Scully, 2016a). Several important physical processes in estuaries, such as longitudinal circulation, lateral circulation, and stratification, are found to have strong influence on hypoxia (e.g., Scully, 2010a; Xia et al., 2010; Murphy et al., 2011; Li et al., 2016).

Chesapeake Bay, located on the East Coast of US, is the largest estuary in US with a length of about 300 km, a total area of tidal waters of about 11,000 $km^2$, and a drainage watershed covering 6 states and accommodating 15 million people (Boesch et al., 2001). The hypoxia in Chesapeake Bay was first documented in the 1930s, and it has worsened over the past half century (Newcombe and Horne, 1938; Hagy et al., 2004). The persistent seasonal hypoxia is generally believed to be caused by the intensive organic carbon decomposition following the spring algal bloom and the isolation of bottom water due to strong stratification during the late spring and the summer (Officer et al., 1984). The hypoxic water volume has remained high since the 1980s, despite intense remediation on the land-based nutrient loading (Boesch et al., 2001). It is generally believed the ecosystem has been strongly disturbed and there was a regime shift around the 1980s, with the fact that hypoxic volume per unit nutrient loading was two or more times greater than that during the period of 1949–1984 (Boesch et al., 2001; Kemp et al., 2009; Liu and Scavia, 2010; Testa and Kemp, 2012).

Many studies have been conducted to understand the mechanisms that control the interannual variation of hypoxia, using monitoring data, empirical models, and sophisticated ecosystem models (e.g., Hagy et al., 2004; Murphy et al., 2011; Testa et al., 2014). It is widely agreed that both the biological processes (e.g., nutrient cycling, algal bloom, and decomposition of organic matters) and physical processes (e.g., stratification, longitudinal circulation, and lateral circulations) contribute to the seasonal and interannual variability of bottom DO condition in Chesapeake Bay. In particular, hypoxic volume has been found very sensitive to nutrient loads, wind-induced mixing, and estuarine circulations, all of which are subject to rapidly changing climate (Hagy et al., 2004; Kemp et al., 2005; Scully, 2010a; Najjar et al., 2010; Jiang and Xia, 2017). Hagy et al. (2004) related the interannual variation of hypoxia to the nutrient loads and river discharge. Scully (2010a) found the interannual variation of hypoxic volume can be much better explained when including the physical forcing, particularly the wind forcing. The physical condition is highly regulated by the large-scale climate variation, such as the North Atlantic Oscillation (Scully, 2010b; Du and Shen, 2015). However, there is still a knowledge gap on the contribution of overall physical condition on the seasonal or interannual variation of DO.

The primary goal of the present study is to investigate the physical control on the bottom DO condition and to examine the long-term trend of physical forcings over the past few decades. To this end, we utilized the long-term observation data (1985–2012) and numerical model simulations of the vertical exchange processes. We applied EOF analysis to the raw observational data to decompose the temporal-spatial variation of the DO in the mainstem of Chesapeake Bay, and explained the primary modes. We scaled the vertical exchange to quantify the overall impact of various physical transport processes (e.g., horizontal advection, vertical diffusion, and vertical advection) and examined its influence on the interannual variability of hypoxic volume in Chesapeake Bay.

## 2. Methods

### 2.1. Data collection

We collected monitoring data from the Chesapeake Bay Program (CBP) for 1985–2012 at 16 stations (Fig. 1), whose locations are approximately evenly distributed along the mainstem of Chesapeake Bay (http://www.chesapeakebay.net). The monthly or semimonthly observation

data of DO, salinity, temperature, and chlorophyll were averaged to obtain the monthly means. Despite the spatial and temporal limitations on the sampling resolution, the available long-term monitoring dataset has been found to give a reliable basis for analysis, not only in Chesapeake Bay (Hagy et al., 2004) but also in other large coastal systems (Bianchi et al., 2010). The dataset has been widely used for a variety of analysis, showing reasonably seasonal and spatial characteristics.

Hypoxic volume based on observation data was collected to illustrate the relative importance of different forcings on the interannual variation of hypoxia. To resolve the limitation of temporal and spatial resolution of the observed data, Bever et al. (2013) combined the numerical model results and DO measurements to generate a more reliable estimation of hypoxic volume for the Bay. In this study, we used the time series of the hypoxic volume from Bever et al. (2013) for the regression analysis between relevant physical or biological parameters (e.g., wind, river discharge, vertical exchange time, nutrient loading, and chlorophyll-*a*) and the interannual variation of hypoxic volume, with an aim to examine the relative percentage explained by different environmental variables on the interannual variation of hypoxic volume.

### 2.2. Empirical orthogonal functions (EOF) analysis

Even though the volume of hypoxic water is a widely used metric to represent the intensity of hypoxia in coastal systems, the integrated hypoxic volume may neglect some important spatial information in regard to the DO dynamics. The raw observational data, on the other hand, still keep useful information that might not have been fully explored. Instead of analyzing the integrated bulk value, we performed decomposition analysis on the original DO data using EOF, a widely used method to reduce the data dimensionality and to extract the primary spatial pattern (Hannachi et al., 2007).

For the EOF analysis, the vertical profiles of DO data were first interpolated into 20 vertical sigma layers, resulting in 320 data points (16 stations × 20 layers) for each month. For the entire 1985–2012 period (336 months), a matrix $F$ with a dimension of 336 × 320 was obtained. Each row of the matrix is one map and each column is the time series for a given depth at a given station. The long-term mean value was subtracted at each data point before performing EOF analysis. Even though hypoxia in Chesapeake Bay only occurs during warmer season and is most intensive during the mid-summer, it is instructive to analyze the observed DO in both cold and warm seasons in order to recognize the possibly different mechanisms in different seasons.

The EOF analysis in this study is based on the singular value decomposition method, which decomposes the data matrix $F$ into the form:

$$F = U\Gamma V^T \quad (1)$$

where $U$ is an orthonormal matrix (336 × 336) of temporal vectors, $V$ is an orthonormal matrix (320 × 320) of spatial vectors, and Γ is a diagonal matrix (336 × 320) storing the eigenvalues.

### 2.3. Quantify the vertical exchange with numerical simulation

With the help of sophisticated hydrodynamic models, the physical processes, particularly those affected by wind and river discharge, have been extensively studied for Chesapeake Bay. It is critical to use an efficient quantitative tool to assess the vertical exchange processes. Here we used the vertical age to scale the effect of overall vertical exchange processes (Shen et al., 2013; Du and Shen, 2015; Du et al., 2017). The vertical age, also known as the vertical exchange time (VET), was computed based on the method proposed by Delhez et al. (1999). This timescale measures the mean time required for the surface water to be transported to a given depth of a given location. A surface water parcel may follow a variety of paths to arrive at a certain location, for example through vertical diffusion, vertical advection, longitudinal circulation, and lateral circulation, depending on the time- and space-varying hydrodynamics. The VET has been successfully used as a straightforward and useful tool to quantify the vertical exchange and examine the physical conditions related to the bottom DO replenishment (e.g., Hong and Shen, 2013; Du and Shen, 2015).

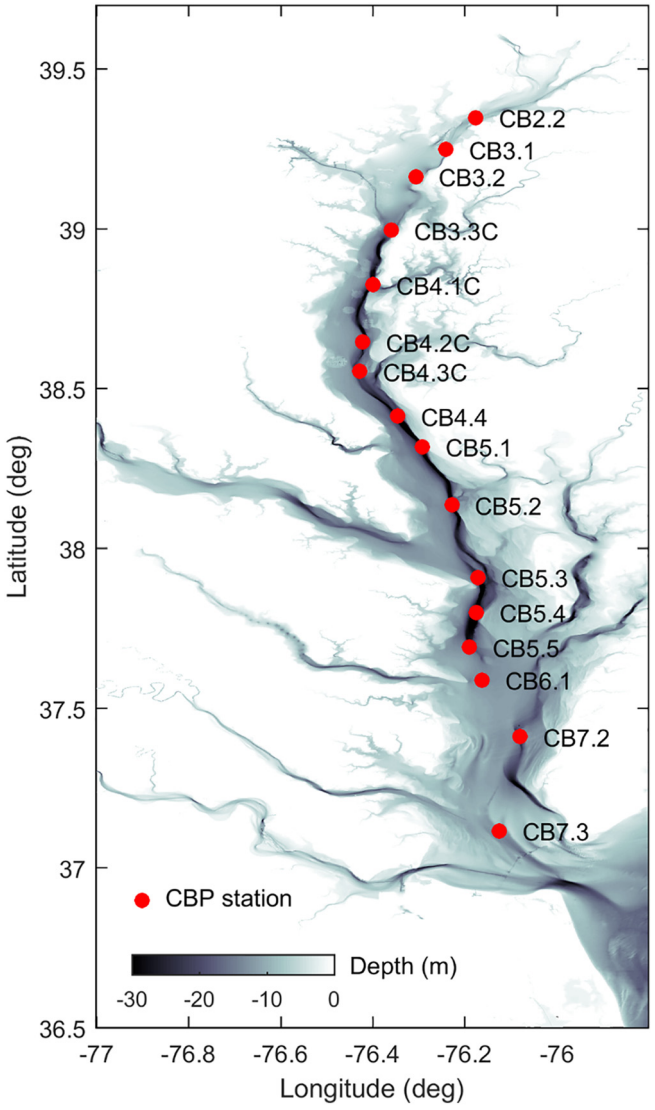


**Fig. 1.** Bathymetry of the Chesapeake Bay and the Chesapeake Bay Program (CBP) monitoring stations along the deep channel in the mainstem.

We used a hydrodynamic model of Environment Fluid Dynamic Code (EFDC) (Hamrick, 1992) to compute the VET from 1985 to 2012 for the Chesapeake Bay (Du and Shen, 2015). This model was driven by the interpolated tidal and salinity observations at the open boundary, reanalyzed wind at the surface, and USGS-measured freshwater discharge from major tributary rivers at the river boundary. The model has been well calibrated in terms of salinity, water level, and tidal current, and has been able to reproduce reliable stratification and destratification processes in both wet and dry years (Hong and Shen, 2012).

## 3. Results

### 3.1. EOF analysis

The first two EOF modes are the dominant components, accounting for 87% and 3% of the DO variance, respectively. The spatial distribution and time series of the two modes are presented in Fig. 2. The first mode

is characterized by all positive values throughout the entire water column, with the largest magnitude in the bottom of the middle Bay (38N to 39N) and the smallest magnitude at the surface (Fig. 2a), indicating a larger variation occurring in the bottom water than in the surface water. The spatial distribution of the first mode has high similarity with the spatial pattern of mean DO values (Du and Shen, 2015). The time series of the first mode is dominated by the seasonal cycles, with the maximum value in the winter and minimum value in the summer.

Not only the noticeable seasonal signal but also the interannual variation of the summer hypoxia is included in the first mode. A significant negative relationship ($r^2 = 0.68$) existed between the interannual time series of the summer mean hypoxic volume and the summer mean of the first mode (Fig. 3). It is therefore very essential to understand the meaning of the first mode. The seasonal cycle is related to various variables, including river discharge, wind field, temperature, nutrient, and algal biomass, all of which have a significant correlation with the first mode time series (not shown) due to their evident seasonality. It was found that the temperature is the best variable to explain the first mode, with it alone explaining 93% of the temporal variation of the first mode (Fig. 4a). However, this doesn't necessarily mean that other variables (e.g., wind field and river discharge) contribute little to this mode, as these variables usually share similar seasonal variations with the temperature and they are not independent statistically.

Despite the strong correlation between temperature and the first mode, the temperature doesn't capture the variability of the first mode when the temperature is higher than 10 °C, resulting in large residuals unexplained (Fig. 4b). This demonstrates that the large variation of the DO near the bottom during warmer season (e.g., summer) cannot be simply explained by the variation of temperature. It is evident that the residuals are randomly distributed, with a maximum variation when the temperature is around 20 °C (Fig. 4b). Since hypoxia in Chesapeake occurs mostly during warmer season, the residuals, especially those under higher temperature, is responsible for the variation of hypoxia. The residuals exhibit a clear seasonal cycle, with a minimum occurring in May (Fig. 4c), which is quite different from temperature seasonality but share similar seasonality with biological activities (e.g., algal blooms, and organic matter decomposition). A regression between the chlorophyll-*a* concentration (averaged over the mainstem and shifted by 2 months) and the residuals shows a significant negative relationship, with $r^2$ of 0.40. This significant relationship suggests biological processes, indicated by the chlorophyll-*a* concentration, play an important role for the DO variation during warmer season. The relationship is less significant if not including the time lag, as it takes time for the newly produced organic matter to settle down to the bottom water and to be decomposed. The largest variation of the residuals occurred when the temperature is near 20 °C (Fig. 4b), which may suggest that intensive algal activities occurred around 20 °C. Because the phytoplankton bloom is highly correlated with the available nutrients, the impact of nutrient discharge is also implicitly included in this first mode.

The spatial distribution of the second mode is characterized by a unique pattern, with positive values in the lower Bay and the surface water of middle and upper Bay, while negative values in the subsurface water of the middle and upper Bay (Fig. 2b). This mode can be attributed to the impact of estuarine circulation and the interaction between the rapidly-changed local geometry and the variation of river discharge. This mode is highly correlated with the Susquehanna River discharge (Fig. 5). As river discharge increases, the estuarine circulation gets stronger (Du and Shen, 2016), which enhances the northward movement of the bottom water, leading to an enhanced oxygen condition in the lower Bay and worsened oxygen condition in the middle-upper Bay (Fig. 3b). Scully (2016b) suggests a large river discharge will also cause a bathymetry-controlled convergence south of the Potomac River mouth and this convergence will lead to a downward advection and vertical mixing of surface oxygen.

The EOF analysis reveals the primary control on the development of the hypoxic condition in Chesapeake Bay, namely the evident seasonal

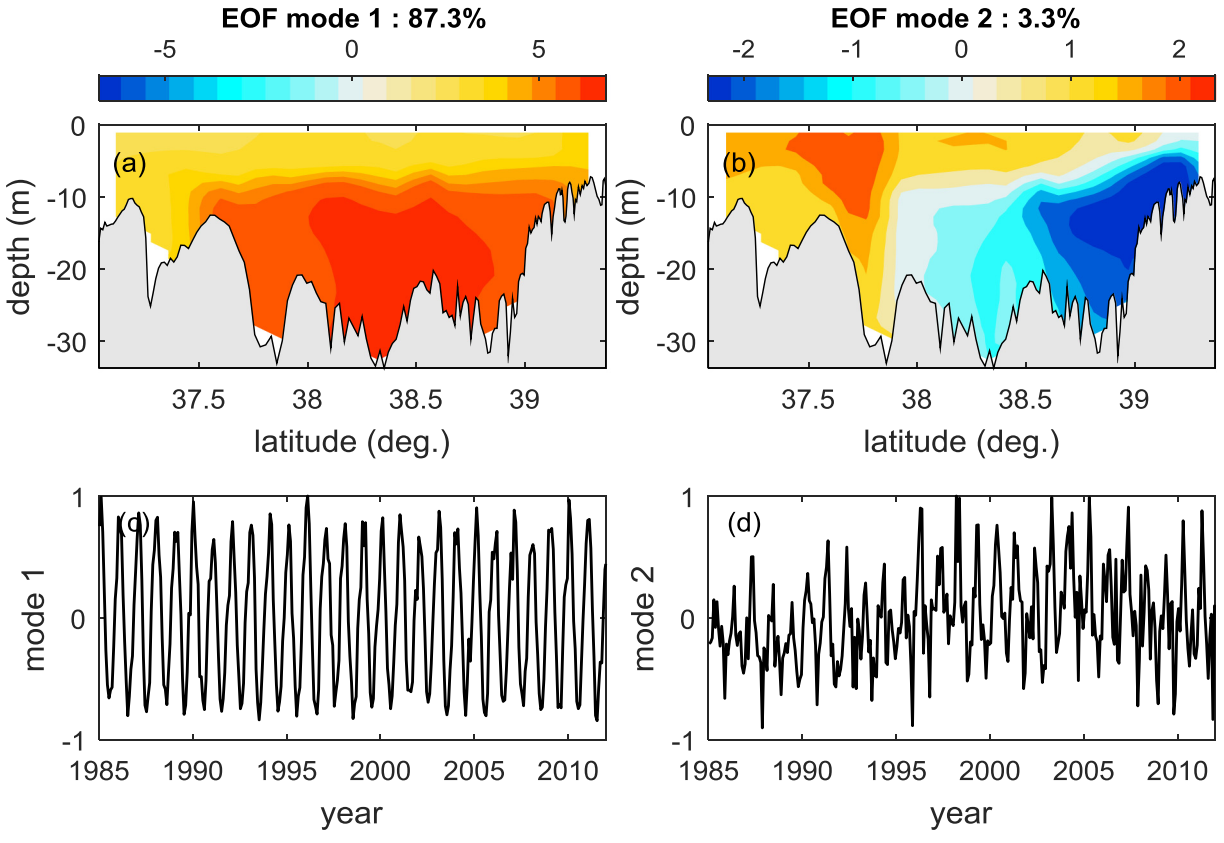


**Fig. 2.** (a–b) spatial distribution of the first two EOF modes of the monthly mean DO along the deep channel section; (c–d) time series of each mode.

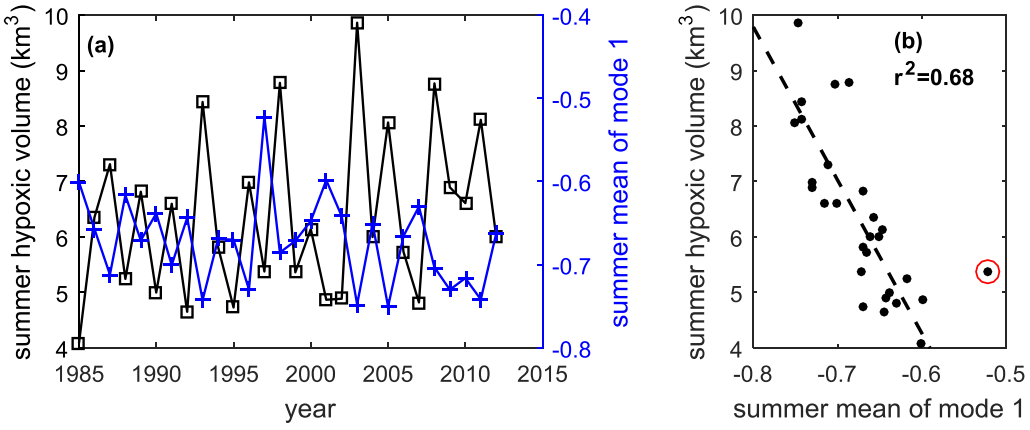


**Fig. 3.** (a) Relationship between the interannual variation of observed summer hypoxic volume and the summer mean of the first EOF mode, and (b) the corresponding scatter plot with a linear regression line. The $r^2$ is 0.57 if the all the 28-year data points are used, and the $r^2$ improves to 0.68 if one data point marked by a red circle in (b) is excluded. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

cycle of the physical condition and intensive biological processes (e.g., change of water column biomass). Even though the temperature is the best variable to explain the seasonal signal of the first mode, the impact of other physical conditions (e.g., stratification, vertical mixing, and estuarine circulation), whose variations share large covariance with the temperature signal, may also be profound under certain condition (Scully, 2010a; Murphy et al., 2011). The EOF analysis not only recognizes the important control from physical conditions but also highlights the essential influence by the biological processes, especially during the warmer season.

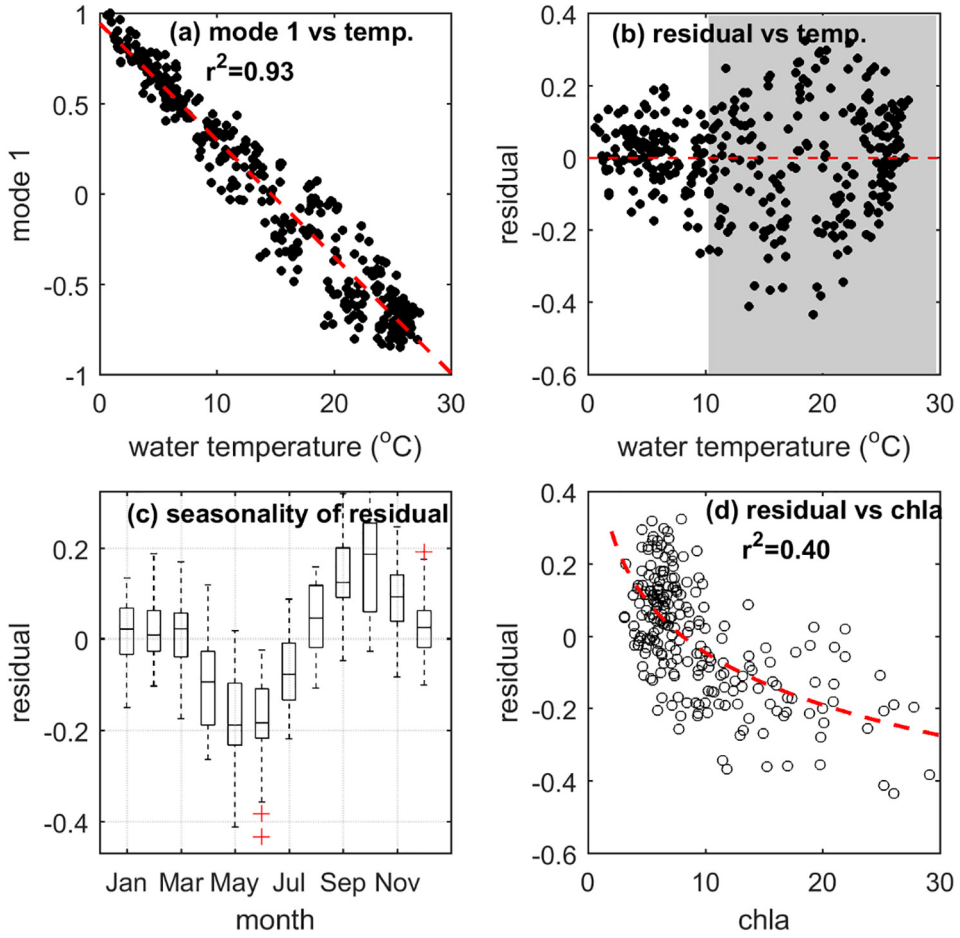


**Fig. 4.** Explanation of the first EOF mode: (a) relationship between the first EOF mode and water temperature; (b) the residual of the linear regression between the first EOF mode and water temperature, with gray shading indicating the large variation of the residual under higher water temperature; (c) the seasonality of the residual shown in box plot for each month; and (d) relationship between residual and chlorophyll-*a* concentration for months with temperature larger than 10 °C. The red dashed lines indicate the linear fit in (a), the line $y = 0$ in (b), and the exponential fit in (d). The red crosses in (c) are the outlier for the box plot. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

### 3.2. Control of vertical exchange on bottom DO

In addition to the temperature's control, the physical transport processes, particularly the vertical exchange, are critical for the bottom DO replenishment and are affected by a variety of processes. Here we used a time scale, namely the vertical exchange time (VET), to quantify the overall effect of various physical transport processes and isolate the physical control on the bottom DO dynamics.

There was a good spatial similarity, both horizontally and vertically, between the VET and the observed DO in Chesapeake Bay (Fig. 6), suggesting a strong control of physical exchange on the spatial distribution of the bottom DO. In the summer of 2005, for example, the hypoxia area is almost identical to the area with the VET larger than 15 days. Although the threshold of the VET values corresponding to hypoxia varies for different years depending on temperature and biological processes, the similarity of spatial patterns persists for every year. Averaged over the summer in 1985–2012, the area with VET larger than 18 days is nearly identical to the observed hypoxic area (Fig. 6c–d).

The spatial pattern of the VET explains some of the most basic characteristics of the hypoxia in Chesapeake Bay. For example, the fact that hypoxia in the Bay starts from the upper Bay near the 39N (Kemp et al., 2005) may be simply attributed to the longest VET in that region. The longest VET near the 39N is mainly caused by two processes. One is the persistent stratification and larger water depth in the middle Bay region compared to the upper and lower Bay. Another is the fact that the location at 39N is at the northern limit of the landward bottom inflow in the lower layer (Goodrich and Blumberg, 1991; Guo and Valle-Levinson, 2007). The bottom inflow of gravitational circulation contributes to the horizontal gradient of the bottom VET along the mainstem, as water parcel ages during the bottom water transport. This gradient is consistent with the bottom DO gradient. Bottom DO in the deep channel of the middle Bay can be replenished by the bottom inflow that carries high oxygen water originated in the lower Bay (Kuo and Neilson, 1987; Kuo et al., 1991). The influence of bottom advective replenishment of DO in middle Bay depends on the magnitude of the bottom inflow as well as the DO consumption rate during the transport.

There is also a clear seasonal cycle of bottom VET, which is caused by the strengthened stratification and weakened bottom inflow during the summer (Du and Shen, 2016). The mean difference between summer and winter VET is about 7 days (Fig. 7a), which means that the bottom water during summer needs 7 more days to be renewed compared to winter. With a mean DO consumption rate of 0.3 mg $L^{-1}$ $day^{-1}$ in the bottom water (Smith and Kemp, 1995), the 7-d difference could result in a DO difference of 2.1 mg/L. The total difference between the mean summer bottom DO (~2 mg/L) and the mean winter bottom DO (~10 mg/L) is about 8 mg/L (Fig. 7b). This gives that the impact of temperature difference due to the change of saturation DO (~4 mg/L) and the VET difference (~2 mg/L) combine to account for about 75% of the seasonal difference, with another 25% possibly due to the seasonality of biogeochemical processes. Even though the percentage estimation is a first-order approximation and it varies from year to year, it is reasonable to state that physical processes are the dominant factor controlling the seasonal variation of bottom DO in Chesapeake Bay.

To understand the high correlation between VET and DO, a conceptual model to estimate the bottom DO was introduced by Shen et al. (2013) and has been successfully applied in Chesapeake Bay (Hong and Shen, 2013; Du and Shen, 2015). In this conceptual model, the bottom DO ($C_b$ in mg/L) is determined by the surface DO ($C_s$ in mg/L) and the product of bottom DO consumption rate ($B$ in mg $L^{-1}$ $day^{-1}$) and bottom VET (day).

$$C_b = C_s - B^* VET \tag{2}$$

With a larger DO consumption rate and/or a larger bottom VET, the bottom DO will be smaller given a same surface DO. During the summer, a bottom VET of 20 days will lead to the hypoxic condition when mean saturation DO is below 8 mg/L and mean bottom DO consumption rate is larger than 0.3 mg $L^{-1}$ $day^{-1}$.

We used 20-day of VET as a criterion to estimate the physically induced hypoxic volume and to examine the impact of physical processes on the interannual variation of hypoxic volume. The estimated hypoxic volume based on VET accounts for 33% of the interannual variability of summer hypoxic volume (Fig. 8). This percentage is smaller than the physical contribution estimated by Scully (2016a) who suggested the physical control contributed to about 50% of the interannual variability of summer hypoxic volume. The lower percentage explained by the VET can be attributed to several factors. Firstly, we did not account for the interannual variation of temperature, which has an impact on the DO saturation at the surface, as we assumed a constant saturation DO of 8 mg/L during summer for every year. Secondly, we used a constant DO consumption rate of 0.3 mg $L^{-1}$ $day^{-1}$ was used as we aim to isolate the impact of VET from other factors. Nonetheless, both Scully (2016a) and our approach reproduced the hypoxic volume at the same order compared to the observed hypoxic volume, and showed the physical modulation on the interannual variation of hypoxia is at the same order as that by the biogeochemical control due to nutrient loading, which explained about 37% of the hypoxic volume (Hagy et al., 2004).

Previous sensitivity tests have demonstrated that VET is highly sensitive to wind strength, especially the southerly wind that is prevalent during summer (Du and Shen, 2015), but VET is not sensitive to river

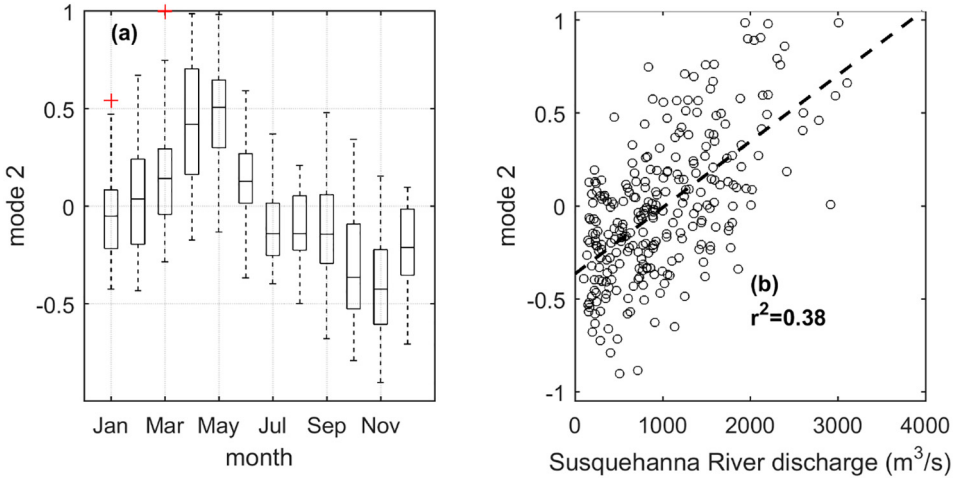


**Fig. 5.** Explanation of the second EOF mode: (a) the seasonality of the second mode and (b) relationship between the second mode and the Susquehanna River discharge shifted by one month.

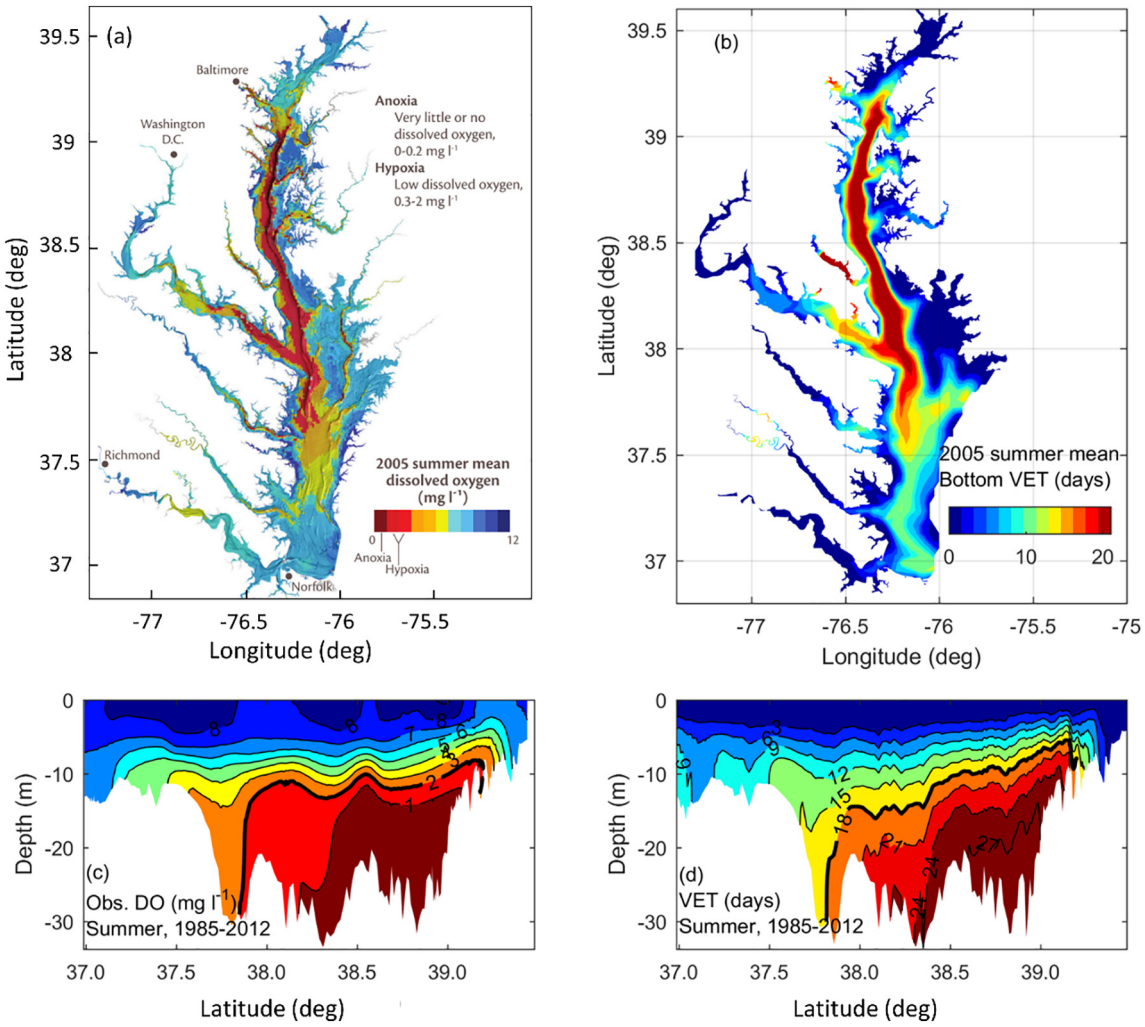


**Fig. 6.** Plan view of observed bottom DO (a) and modeled vertical exchange time (VET) (b) for the summer of 2005; longitudinal view along the main channel of observed DO (c) and modeled VET (d) for summer averaged over 1985–2012; (a) is from Chesapeake Bay Program, and (c) is based on the long-term DO data collected from Chesapeake Bay Program.

discharge (Hong and Shen, 2013), consistent with the conclusions from previous empirical regression and ecosystem model simulations (Scully, 2010a; Murphy et al., 2011; Li et al., 2016). Li et al. (2016) demonstrated that the negative impact of the weakened vertical diffusion on the bottom DO during a larger discharge period can be largely compensated by the positive impact of the stronger longitudinal advection replenishment. The high relationship between hypoxic volume and river discharge observed in the past few decades (Hagy et al., 2004; Murphy et al., 2011) can be attributed to the change in nutrient load rather than that in stratification.

### 3.3. Relationship between hypoxic volume and various environmental variables

As hypoxia is caused by high biogeochemical DO consumption and weak physical exchange, any climatic or hydrological factors that affect either the biological or the physical processes could exert an influence on the hypoxic condition. These variables include the temperature, freshwater discharge, stratification, mean sea level, wind speed, wind direction, nutrient loading and so forth. Most of these variables may directly affect the physical exchange by altering either the horizontal or vertical exchange.

Several linear regressions between the hypoxic water volume over 1985–2012 and hydraulic or climatic variables were conducted. Total hours of westerly wind, chlorophyll-*a* concentration, nutrient loading, and vertical exchange time have significant positive correlation with the hypoxic volume whereas temperature and mean sea level does not have a significant correlation with the hypoxic volume (Fig. 9). Two of the most profound controls are from the nutrient loading and vertical exchange. The variance of hypoxic volume accounted for by VET is same to that by nutrient loading. This suggests an almost equal contribution on the variation of hypoxic volume from the variation of physical exchange and the nutrient-related biological processes.

The relationship between the hypoxic volume and temperature is not significant, which can be well explained by the above EOF analysis. Even though the temperature explained 93% of the first EOF mode, there are considerable residuals especially when the temperature is high (Fig. 4b), indicating that bottom DO variation cannot be well explained by the variation of temperature during the warmer season. One possible reason is the highly variable biological condition (e.g., amount of organic matter, respiration in the water column, and sediment oxygen demand) during the warmer season. Nonetheless, the poor correlation between temperature and the hypoxic volume cannot be interpreted as little impact from the water temperature. Instead, it is believed that the bottom DO is more sensitive to the biological control in the warmer season. A higher water temperature tends to amplify the negative impact of excessive input of organic matter that come from either the external loading or phytoplankton production within the system.

Despite large variabilities, several variables show significant long-term trends (Fig. 9), with an increasing trend for temperature (not shown), VET, mean sea level, and chl-*a*, which suggests that the physical and biological conditions have worsened the hypoxia during the past

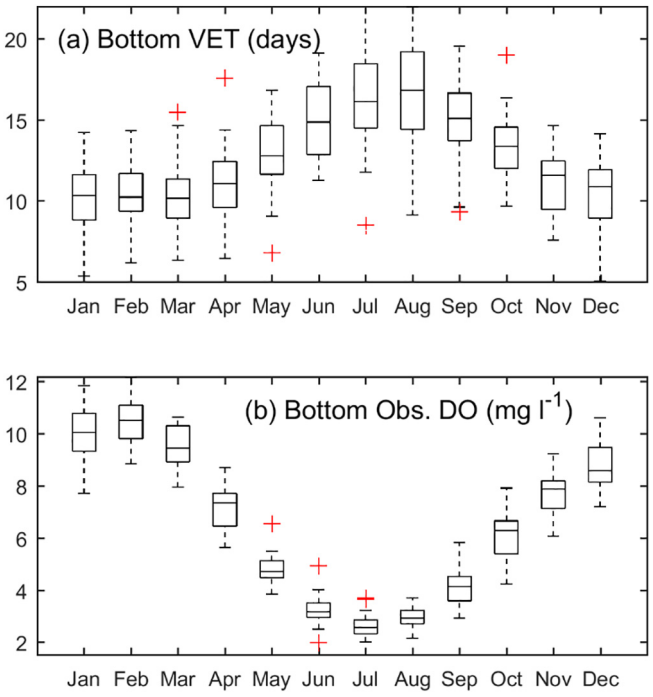


**Fig. 7.** Seasonality of the modeled bottom VET (a) and observed bottom DO (b), both of which are averaged over the deep channel section. For the box plot, the black lines within the rectangles denote medians, black rectangles denote the first and third quartiles, dashed lines denote the upper and lower whiskers, and red crosses denote the outliers. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

three decades. The temporal trend for the wind and VET became more evident since 2000 (Fig. 9), with a noticeable decrease of wind speed and increase of VET. The increasing trend of VET and water temperature suggested a worsened physical condition in the past few decades. The worsened physical condition has wide implications, for instance, making the Bay to become more sensitive to a larger nutrient loading. The worsened physical condition will also amplify the negative impact of eutrophication. With the same level of eutrophication, a worsened physical environment will make the system more susceptible to the hypoxia. To remediate the hypoxia to an acceptable level, more nutrient loading reduction than previously thought may be required in the future.

## 4. Discussion

### 4.1. Biogeochemical vs physical control on hypoxia

Hypoxia occurs as a combined result of the biogeochemically-controlled persistent DO consumption and physically-controlled limited oxygen replenishment. Chesapeake Bay is a typical partially-mixed estuary with a clear seasonal cycle and a large interannual variability of both physical condition and biogeochemical processes. The EOF analysis, numerical simulations, and statistical analysis conducted in this study consistently suggest a comparable or even equal importance of biogeochemical processes and physical processes on both the monthly and interannual variation of hypoxia in Chesapeake Bay.

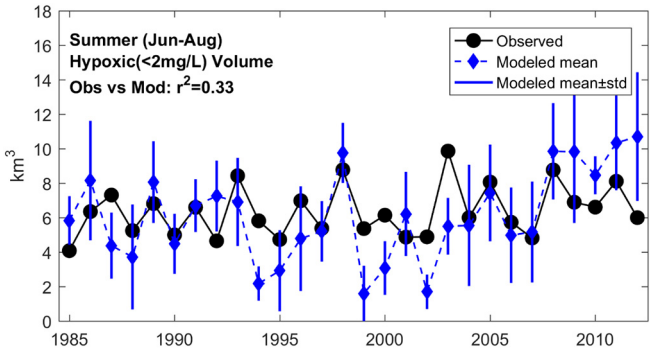


**Fig. 8.** Interannual variability of observed hypoxic (<2 mg/L oxygen) volume and physically induced hypoxic volume (>20 days VET) in summer.

The biogeochemical condition, indicated by chlorophyll-*a* concentration and directly related to the nutrient loading, explains a large portion of the interannual variation of the summer hypoxic volume and the monthly variation of the bottom DO (Figs. 4, 9). Besides the high variability of winter-spring river discharge and January–May nutrient loading, the diversified sources of organic matter also contribute to the high variability of the biogeochemical condition. Both the spring algal bloom stimulated by high winter-spring river discharge (Smith and Kemp, 1995) and the summer algal bloom, due to the fast recycling of nutrients and the phosphate and inorganic nitrogen released from the sediment under hypoxic condition, provide a considerable amount of labile organic matter to the bottom water. The organic matter in the deep middle Bay can come from four main sources, namely local algal bloom, the bottom advection that bring the organic matter from the lower Bay, the terrestrial organic matter delivered by the Susquehanna River and tributaries discharging into the middle-upper Bay, and the carryover of the previous years' organic matter buried at the bottom (Fig. 10). The transport of these materials occurs not only in summer but also in other seasons (Lee et al., 2013), and the material distribution highly depends on release location (Du and Shen, 2017). Material transport during the winter and early spring may also contribute to the abundance of organic matter in the deep middle Bay in the summer. Diversified sources of organic carbon might make the biogeochemical condition variable, spatially and temporally, as various processes could contribute to the change and are subject to the external perturbations.

The physical condition, on the other hand, also has a profound impact on seasonal and interannual variation of DO condition. The high variability of relevant physical condition comes from the relatively complex estuarine hydrodynamics. Chesapeake Bay is characterized with multiple tributaries, clearly defined mainstem, large shallow area, relative deep bathymetry in the middle Bay, and relatively shallow bathymetry in the lower Bay. The geological setting makes the dynamics, particularly the vertical exchange processes, highly variable in the Bay's mainstem, with both longitudinal circulation and lateral circulation contributing to the bottom DO replenishment. Variables, including temperature, river discharge, wind field, residence time, and mean sea level, affect the physical condition. These variables have shown large variability over the past few decades (Fig. 9; Hagy et al., 2004; Scully, 2010b; Du and Shen, 2016). Many of these variables affect the vertical exchange directly. For example, wind has been recognized to have a significant control on the bottom DO variation through modulating not only the vertical mixing but also the lateral and longitudinal exchanges (Scully, 2010a). The freshwater discharge, however, has proved to have less control on the vertical exchange (Hong and Shen, 2013; Li et al., 2016) but have a great correlation with the nutrient loads. Some variables, for example, temperature, affect not only the physical exchange but also the biogeochemical activities. For instance, high temperature will reduce the DO solubility, increase the stratification, enhance the organism metabolism, enhance the nutrient recycling, and lower the organism oxygen tolerance.

Overall, the physical control and biological control on the interannual variation of hypoxic condition are equally important in Chesapeake Bay over the past few decades and possibly continue to competing with each other in the future.

### 4.2. Physical condition in the past and its impact on hypoxia in the bay

Several variables related to the physical condition are changing, either slightly or noticeably, over the past few decades, including

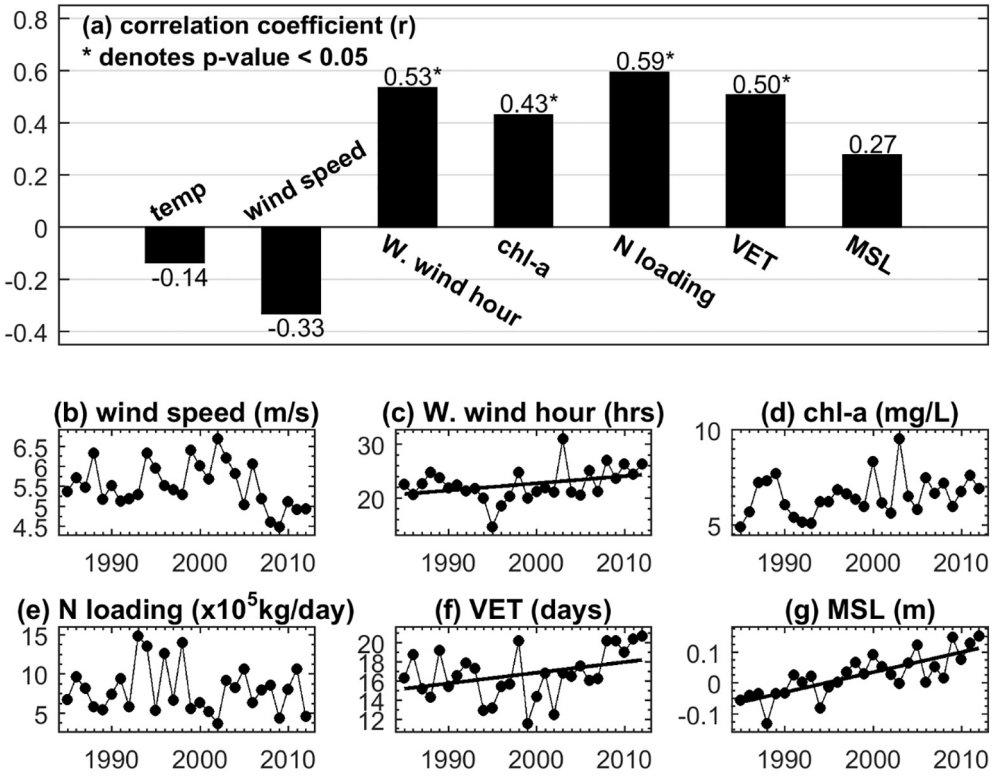


**Fig. 9.** (a) Correlation coefficient (r) between the observed summer hypoxic volume and summer water temperature (from CBP), summer wind speed (from NARR), summer westerly wind hour (from NARR), summer chl-*a* concentration (from CBP), January–May nutrient loading (from USGS), summer bottom VET (from numerical simulation), and summer mean sea level (from NOAA at CBBT). The interannual variations of selected variables are shown in (b)–(g).

temperature, river discharge, wind field, and mean sea level (Fig. 9; Najjar et al., 2010; Scully, 2010b; Murphy et al., 2011). The clear increasing trend of VET, water temperature, and mean sea level, and decreasing trend of wind speed (esp. after the year 2000) suggest a worsened physical condition in the Chesapeake Bay in the past few decades.

The worsened physical condition may partly be a reason for the high hypoxic volume since the 1980s. Since the 1980s, the hypoxic volume remains high, and, more importantly, the hypoxic volume per nutrient load has doubled compared to the period of 1949–1984 (Boesch et al., 2001). Even with intensive nutrient loading remediating efforts, the hypoxic volume since the 1980s has much less variability than before. There is a noticeable change of the physical condition, with the Bermuda high index shifting to negative values since the 1980s (Scully, 2010b), and the change of the physical condition has manifested in the wind field.

### 4.3. Physical condition in the future and its impact on hypoxia in the bay

Climate change (e.g., global warming, accelerated sea-level rise, altered precipitation pattern, changed ocean and shelf currents, and altered timing and intensity of hurricanes) has reshaped coastal systems in many ways. Global climate changes will likely result in higher water temperatures, stronger stratification, and increased input of freshwater discharge and nutrients to coastal waters in many areas of the globe (Rabalais et al., 2009, 2010). Particularly, the increased water temperature alone is sufficient to worsen the DO condition through lowering the oxygen solubility, strengthening the stratification, increasing metabolism rate, fastening nitrogen cycling, lowering the DO tolerance for aquatic organisms, and altering the timing and intensity of algal bloom (Meier et al., 2011; Altieri and Gedan, 2015). It has been projected that 90% of the current coastal dead zones will experience at

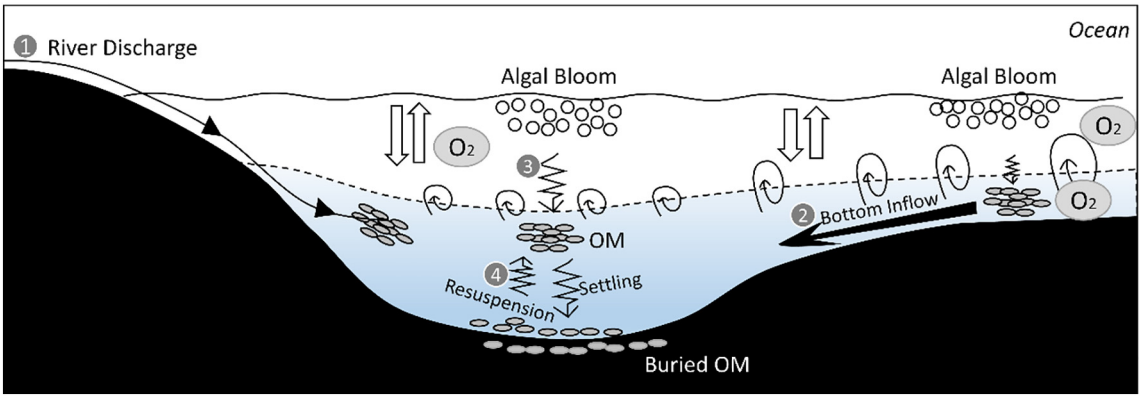


**Fig. 10.** A sketch showing the four sources of organic matter in the deep middle Bay. Four organic matter sources include terrestrial organic matter carried by river discharge, primary production settling down to bottom layer, organic matter from the lower bay carried by bottom inflow, and resuspension of buried organic matter.

least 2 °C increase of water temperature by the end of 21st century (Altieri and Gedan, 2015).

There is increasing evidence showing that the worsened physical condition also contributes to the increasing hypoxia (e.g., Carstensen et al., 2014; Jenny et al., 2014; Altieri and Gedan, 2015). Depending on the relative importance and the variability of physical dynamics in different coastal systems, the physical condition may have played a role with different significance in the change of hypoxia.

As result of climate change, Chesapeake Bay is projected to have an increased spring river discharge, a moderate sea-level rise, a large variation of wind field, and fewer but stronger hurricanes in future (Najjar et al., 2010). The river discharge has proved to be highly linearly related to the hypoxic volume through the change of nutrient loads (Hagy et al., 2004). Its impact on the physical condition, however, is limited. With increased river discharge, weakened vertical diffusion may be compensated for by the enhanced horizontal advection replenishment from the shallow lower Bay waters (Li et al., 2016). The hurricanes' impact is profound, which could well-mix the entire water column even in the deepest channel when the wind speed is large enough (Li et al., 2006). The impact of the hurricane is however hard to predict, as one doesn't know exactly the trend of the hurricanes in the future, and most importantly, the timing and path of the hurricanes. A sea-level rise of 2.7–4.5 mm $yr^{-1}$ in Chesapeake Bay has been observed over the second half of the 20th century (Zervas, 2001). The larger sea-level rise rate in Chesapeake Bay compared to the global mean has been attributed to the land subsidence (Boon et al., 2010) and the sea-level rise will cause spatially varying tidal and estuarine response in Chesapeake Bay (Du et al., 2018). Nevertheless, consistent with many other estuaries, sea-level rise will enhance the salt intrusion and the stratification in the middle-upper Bay (Hong and Shen, 2012). However, the bottom exchange flow, which is proportional to the cubic of the water depth (MacCready, 2004), will also be enhanced, which would enhance replenishment of DO from the lower Bay.

Overall, Chesapeake Bay in the future is likely to have warmer and more stratified water column. Considering the uncertain recovery of the benthic community and the nonlinear response to a change of nutrient loading, Chesapeake Bay is likely to experience more serious seasonal hypoxia in coming decades. The physical condition is expected to be worsened, which would make the system more sensitive to the nutrient and organic matter loading. If the current hypoxic condition maintains, the carryover of organic matter in the bottom sediment may be subject to resuspension by intensified hurricanes. The nutrient remediation strategies based on current condition may overestimate the assimilation capacity of the system in the future.

## 5. Conclusion

The physical condition is commonly agreed to have a great influence on the seasonal hypoxia in Chesapeake Bay. EOF analysis of the long-term DO data, numerical calculation of the vertical exchange processes, and statistical analysis reveal the importance of physical control on the spatial distribution, seasonality, and interannual variation of hypoxia in Chesapeake Bay. The spatial pattern and seasonality of DO in Chesapeake Bay are determined by physical forcings and processes (i.e., temperature and vertical exchange), while the interannual variations of DO, particularly during the warm seasons, are equally regulated by physical and biological processes. The interannual variation of vertical exchange explains almost equal percentage of the interannual variability of the hypoxic volume, comparable to the percentage explained by the variation of nutrient loading. The first EOF mode, which includes the interannual variability of summer hypoxic volume, is well explained by the variation of temperature. The temperature's variation, however, cannot well explain the interannual variation of hypoxic volume, which is more directly determined by the interannual variation of the vertical exchange and the nutrient-controlled biological activities. The biological control is more profound during the warmer seasons, suggesting that a higher water temperature is likely to increase the sensitivity of the estuarine system to the negative impact of eutrophication and excessive input of organic matter either from external sources or produced within the system.

The physical condition, represented by VET and temperature, has been worsened since the 1980s, which contributes to the increase of hypoxia volume. With the rapid global warming, accelerated sea-level rise, and shifting of large-scale climate systems, we hold the perspective that a worsened physical condition may have contributed to the increasing hypoxia in Chesapeake Bay in the past and possibly in the future. The worsened physical condition will amplify the negative impact of human-induced eutrophication, implying that a more disproportional nutrient reduction than previously estimated may be needed in order to reduce the hypoxic condition to a satisfactory level in Chesapeake Bay.

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